UNCLASSIFIED

AD NUMBER
ADA800657
CLASSIFICATION CHANGES
TO: unclassified
FROM: restricted
LIMITATION CHANGES
TO: Approved for public release; distribution is unlimited.
FROM: Distribution authorized to DoD only; Foreign Government Information; JUN 1945. Other requests shall be referred to British Embassy, 3100 Massachusetts Avenue, NW, Washington, DC 20008.
AUTHORITY
DSTL, AVIA 6/8641, 4 Aug 2009; DSTL, AVIA 6/8641, 4 Aug 2009

THIS PAGE IS UNCLASSIFIED

REEL

C 32

FRAME

792

D52.419/976

0197713

NOT SUITABLE FOR FURTHER DISTRIBUTION

BRITISH RESTRICTED Equals
UNITED STATES RESTRICTED

Class No. 621.43.068.2 : 532.525.001.2

Technical Note No. Eng.352

Technical Note No. Eng.352

June, 1945.

ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

Note on exhaust actuated air ejector design

- by -

J.Lukasiewicz, Inz.Mech., B.Sc.

R.A.E. Ref: Eng./2210-7/JL/140

SUMMARY

The available reports on exhaust ejectors used as pumps or thrust augmentors are listed and a survey of the existing data is given. In this Note the general effect of the main variables on ejector performance is shown and theoretical and experimental ejector performances are compared. The data for estimating the basic exhaust thrust and the optimum exhaust nozzle area are considered and it is concluded that the thrust but not the nozzle area can be estimated adequately at present. Future theoretical and experimental work on ejectors is suggested, and includes, in the first instance, the development of a uniform theory of ejectors regarded as thrust and pumping devices.

CONTENTS

RESTRICTED

16 R-4694-45.

1. Introduction

One of the proposed methods of using aero-engine exhaust gas energy is to embody ejectors as cooling-air pumps and thrust augmentors. As will be seen from the attached incomplete Bibliography List, a considerable amount of experimental and theoretical work has been done on exhaust gas ejectors. The purpose of the present note is to indicate the extent of the data available for ejector design and to suggest what further work appears to be needed at present.

2. Outline of the theoretical analysis of ejectors

2.1. Equations

The theoretical treatment of ejectors, although varying in detail, is usually based on four steady-flow equations: 2, 9, 18, 19.

(i) equation of continuity

(ii) equation of momentum

(iii) equation of energy

(iv) equation of state

2.2. Assumptions

In order to apply the above equations in a simple way it is usual to assume:

(i) one-dimensional, adiabatic and frictionless flow for air and exhaust gas,

(ii) complete mixing attained at the ejector exit,

(iii) incompressible flow for air, density being a function of the temperature only,

(iv) when a diffuser is incorporated into the ejector system, a certain "diffuser efficiency".

2.3. Design factors unaccounted for by theory

In the outlined theoretical treatment, certain important design factors are omitted, such as:

(i) ejector length, which has the double and opposite effects of improving the mixing but increasing the friction,

(ii) shape of the ejector and the exhaust gas nozzle cross-section,

(iii) location of the exhaust gas nozzle,

(iv) number of stages in which the mixing has to be accomplished (only the final ejector cross-sectional area appears in the equations).

2.4. Intermittency of the exhaust gas flow

The outlined theoretical treatment can be applied to the steady-flow ejectors e.g. such as were tested in the compressed-air experiments.[11, 21, 25] When dealing however with the actual aero-engine exhaust ejectors, in order to account for the intermittency of the exhaust gas flow, a mean effective exhaust gas velocity obtained from the measured exhaust gas thrust, has to be used.[23] A corresponding exhaust gas temperature can be calculated from the equations of continuity and of state, or assumed.

2.5. Main Variables

In the theoretical analysis of the ejector performance the following variables are usually considered:

(i) $\mu = M_c/M_e = \dfrac{\text{cooling air mass flow}}{\text{exhaust gas flow}}$

(ii) Δp = pressure difference across ejector = (static pressure at ejector exit) − (stagnation pressure in front of the ejector)

Note: stagnation pressure is usually taken as the static pressure behind the engine, where the air velocity is small.

(iii) $\alpha = A_c/A_e = \dfrac{\text{ejector cross sectional area}}{\text{exhaust nozzle cross sectional area}}$

(iv) $\theta = F/F_0 = \dfrac{\text{thrust at ejector exit}}{\text{thrust given by exhaust nozzle only}}$

2.6. Effect of resistance

It should be noted that μ and Δp have not, in all cases, the same meaning. For the conditions of ground cooling, i.e. with zero ram in front of the engine, Δp is equal to the pressure drop across the engine and thus, for constant engine operating conditions (F_0 = const.), μ is a function of Δp, their relationship being given by the hot flow calibration of the engine. In this case the optimum ejector arrangement is that which gives maximum Δp (and μ). On the other hand, if the ejector is located after a variable resistance to flow or if ram is applied in front of the resistance, then μ is not solely a function of Δp. The best arrangement is that which, for a given μ, gives the highest Δp (or $-\Delta p$ in case of [illegible]). This method is more general, since it provides information on the effect of μ.

RESTRICTED

2·7 MAIN FUNCTIONS — THE RELATIONSHIP OF THE FOREGOING VARIABLES FOR UNIFORM CROSS SECTION EJECTORS CAN BE SHOWN DIAGRAMMATICALLY AS FOLLOWS :-

2·71 IN FIG. 1. THE INFLUENCE OF THE EXHAUST EJECTOR NOZZLE ON EJECTOR PERFORMANCE IS SHOWN, FOR CONSTANT EJECTOR CROSS SECTIONAL AREA A_a.[19] CURVES FOR CONSTANT ENGINE POWER ARE DRAWN.

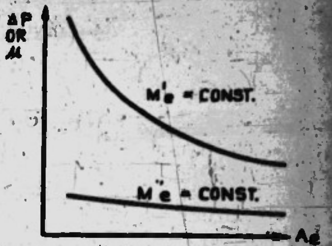

FIG. 1. A_a = CONST. $\mu = f(\Delta P)$, $M'_e > M''_e$

2·72 IN FIGS 2 & 3 THE INFLUENCE OF α (OR A_a, A_e BEING CONSTANT) ON EJECTOR PERFORMANCE IS SHOWN. FIG. 2. APPLIES TO THE CASE OF CONSTANT RESISTANCE, $\mu = f(\Delta p)$ [19] WHILE IN FIG. 3. THE RESISTANCE WAS VARIED [18].

IN BOTH CASES RAM = 0.

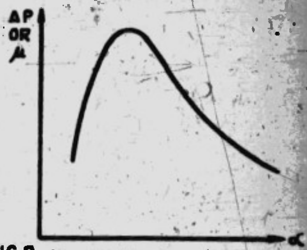

FIG. 2. A_e = CONST. F_o = CONST.

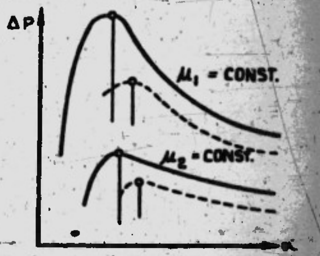

FIG. 3. A_e = CONST. F_o = CONST. -- EXPERIMENTAL CURVES

2·73 THE INFLUENCE OF RAM ON THE EJECTOR ACTION AS A PUMP IS ILLUSTRATED IN FIG. 4, WHICH SHOWS THAT THE EJECTOR PUMPING GAIN DECREASES WITH RAM. (IE. FLIGHT SPEED) [19]

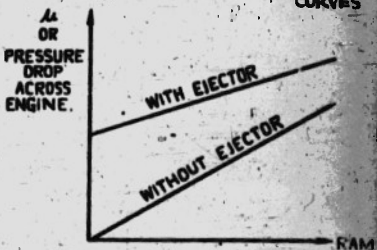

FIG. 4 $A_e . A_a . M_e . F_o$ = CONST

2·74 A SIMILAR EFFECT OF RAM (IE. FLIGHT SPEED) ON EJECTOR THRUST IS SHOWN IN FIG 5 & IS COMPARED WITH THRUST OBTAINED FROM COOLING AIR & EXHAUST GAS SEPARATELY.[2] FIG. 5. SHOWS THAT EJECTOR IS A THRUST AUGMENTOR AT LOW SPEEDS ONLY.

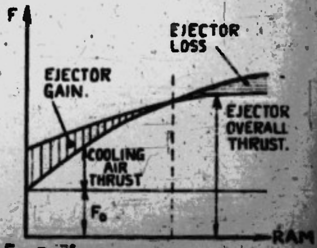

FIG. 5. F_o, M_e, M_a, α = CONST

2.7.5 Both Figs.4 and 5 indicate that maximum ejector performance is obtained at zero r.a.s., i.e. at ground cooling conditions.

3. Experimental data available: Exhaust gas nozzles

3.1. Critical nozzle area

Taking into account net thrust as given by propeller and exhaust gas, it does not pay in general to decrease the exhaust nozzle area beyond the critical size, at which the engine B.H.P. starts to drop.[10,23] From the point of view of the ejector performance the smallest possible nozzle is required [19] (see 2.7.1). and thus the critical size should be used. The theoretical determination of this optimum nozzle size for an engine working under specified conditions does not seem at present possible; the only available method[23] is based on one set of tests on a poppet-valve engine and its general application, in view of the results of other similar tests[10], is doubtful.

It seems therefore desirable to make an attempt to establish a satisfactory correlation of the available data on the critical nozzle area, so that it could be determined beforehand without resorting to experimental methods.

3.2. Exhaust gas momentum

3.2.1. It has been already pointed out (2.4) that in order to apply the steady flow theory to the exhaust gas ejectors, it is necessary to introduce the "effective" exhaust gas velocity, as given by measured exhaust gas thrust and mean exhaust gas mass flow. It seems that a satisfactory method of correlating the experimental data over a wide range of engine characteristics and operating conditions has been developed[19, 23].

It would be desirable to apply this method to the available experimental data[6, 10, 19] and thus to establish finally its reliability.

3.2.2. Various methods of experimental exhaust thrust measurement were used and they can be divided in two main groups:

(a) by use of a target, the function of which is to change the direction of the exhaust gas momentum by 90° [10, 23] and

(b) by pitot-static pressure readings at the exhaust gas nozzle exit[8].

It appears that, except in one case[19], no efforts were made to compare the results obtained by the two methods; such a correlation of the two would be useful, the (b) method being much simpler to apply in practice*.

3.3. Shape of the exhaust nozzle

This factor does not come in the theoretical analysis and its influence has to be determined experimentally. Only one such set of tests is available[18] and they definitely indicate that a flattened, rectangular nozzle gives better ejector performance than a nozzle of aspect ratio 1:1. The optimum nozzle aspect ratio depends on the ejector arrangement and seems to be of the order of 10 to 15.

---

* Apart from the available data, the single-cylinder tests of the R.A.E. Low Drag Power Plant should provide the necessary results for comparison.

3.4. Position of the exhaust nozzle

It appears that the location of the exhaust nozzle at the ejector entry has only slight influence on the ejector performance[18,21].

4. Experimental data available: Ejectors

4.1. Mixing section

Several investigators have come to the conclusion[7,13] that a uniform cross-section mixing length is the most satisfactory (also called "straight mixing section"). Thus in the various exhaust-gas ejector tests only this type was considered, sometimes with a diffuser attached to the straight section. The remarks which follow apply to this type of ejector.

4.2. Types of tests

The available experimental data can be divided according to the types of tests into

(a) steady flow tests (with compressed air or constant pressure combustion chamber)[11,12,21,25].

(b) intermittent flow tests (usually on actual aero-engines)[17,18,19,20,21]

and according to the purpose of tests into

(a) tests of ejectors as pumps[12,17,18,19,20].

(b) tests of ejectors as thrust augmentors[11,12,20,21,25].

In the majority of cases the tests were carried out with zero ram, i.e. at ground cooling conditions for the buried installations. Thus only in one instance both thrust and pumping aspects of the intermittent flow ejector have been investigated and then only very briefly.[20] It seems therefore that futher tests of this type would be useful*.

4.3. Actual ejector performance

The comparison of the theoretical and experimental ejector performance is indicated diagrammatically in Fig. 3 above. The max. Δp are smaller than the ones predicted by theory and the optimum α is bigger than the theoretical one; it is independent of the ejector length[18].

In most experiments the qualitative agreement with theory is reasonably good; the quantitative agreement varies, the optimum ejector giving usually Δp values of the order of 0.7 to 0.8 of the theoretical ones (for same area ratio α).

4.4. Suitable ejector proportions

It has been pointed out already that the ejector length does not come into the theoretical analysis. Its influence is usually expressed in the experimental results by the factor L/D, where L = ejector length and D = hydraulic diameter = $\dfrac{4\,A_a}{\text{perimeter}}$. It appears that for straight

---

* Single-cylinder tests of the R.A.E. Low Drag Power Plant will be of this type.

single-stage ejectors, for both thrust augmentation and pumping purposes, the optimum L/D value lies between 6 and 10 for α varying from 5 to 50. The lower L/D values seem to apply to the higher α and μ values[18,19,21].

4.5. Multi-stage ejectors

From test results it appears that, both from the pumping and thrust augmentation point of view, better results are obtained with multi-stage ejectors, in which the mixing process occurs in several steps and that three is the optimum number of stages[19,21].

The optimum overall length of the multi-stage ejectors seems to be smaller than that of the corresponding single-stage arrangement.

Little information is available on the optimum multi-stage ejector design. However, since in practice it will be seldom possible to use more than two mixing stages and in view of the considerable difficulty in formulating any rules for multi-stage ejector design, it is not suggested that any general experimental work should be undertaken in this direction.

4.6. Ejectors with diffusers

Diffusers fitted at the exit of the straight ejectors increase the pumping performance, this being especially marked at low α values. It appears that for the same overall length it definitely pays, for pumping, to fit diffusers in small α ($\approx$ 10) ejectors; for high α values the diffuser gain is smaller and appears only at high L/D values and the optimum L/D value is considerably higher than that for ejectors without diffusers; hence, in this case, if the length is limited, the diffuser does not pay[19].

The diffusers usually fitted are of a cross-sectional area ratio of 2 to 3 and a divergence angle of about 10°.[18,19]

4.7. Rectangular ejectors

Most of the tests were made with the circular cross-section ejectors. In one instance[18] however, ejectors of various rectangular sections were tried; it appears that the best pumping results were obtained with ejectors of aspect ratio 3, although there was only a slight improvement as compared with the results of the ejectors of aspect ratio 1 or 5.

4.8. Curved ejectors

Slight bends (15°) in the mixing section do not impair noticeably the ejector performance[18].

4.9. Ejector entry

It appears that there is a definite gain in using a bell-mouthed or conical ejector entry up to 1.5 ejector diameter. No gain is obtained by using still bigger diameters[21].

4.10. Grouped ejectors[17]

Most of the tests were carried out with ejectors actuated by the exhaust gas issuing from one or two cylinders. In one case[17] however, the effect of individual and grouped ejectors was investigated. In the latter arrangement the exhaust stacks were combined in groups of three, the firing intervals of the cylinders in each group being spaced equally.

It was found that for the same overall A_a the grouped ejectors gave better results (Δp and μ); where the total area of the triple ejectors was equal to 1/3 of the total area of the individual ejectors, the latter gave better performance.

5. Suggested future work on ejectors

Throughout this Note certain suggestions have been made on the future theoretical and experimental work on the exhaust-gas ejectors to be undertaken. These and some additional proposals are here collected. It is thought however that before starting any of the proposed tests the theoretical work outlined below should be first completed.

5.1. Theoretical work

5.1.1. In connection with the application of the exhaust-gas ejectors to air-cooled aero-engines it would be useful to develop a comprehensive analysis of ejectors as thrust augmentors and air pumps: this can be readily done by combining the available theoretical data. Such a uniform theory should be based on dimensionless variables and should be adaptable to any engine hot-flow and exhaust characteristics; graphical methods of solution should be used.

5.1.2. A satisfactory method for the theoretical determination of the critical exhaust-gas nozzle area should be developed (see 3.1).

5.1.3. The reliability of estimating the exhaust-gas momentum should be checked against the available experimental data (see 3.2).

5.1.4. Pitot-static pressures and target methods of thrust measurements should be compared by new tests if necessary.

5.2. Experimental work*

5.2.1. Tests in which both pumping and thrust ejector characteristics with intermittent flow would be investigated seem to be needed. Practically no data is at present available on the correlation of the ejector thrust theory and practice.

5.2.2. Influence of the divergence (diffuser) and convergence of the ejector exit section should be investigated, in parcticular with respect to thrust.

5.2.3. The envisaged test rig would consist of a single-cylinder liquid-cooled unit, the exhaust of which would be used to actuate air ejectors. The ejectors should be connected to a surge tank placed after an air blower, which would provide considerable ram pressures. Upstream of the ejector various resistances, representing the engine cylinders, would be fitted. Ejectors of various cross-sectional areas should be tested, each consisting of several segments so that a number of different overall lengths would be tried. Also ejectors of each size should be fitted with a variable exit area (nozzle or diffuser effect).

The following main measurements would be taken:

(1) air-flow (by means of pitot-static traverse or orifice),

(2) exhaust gas flow,

---

* see also 5.1.4.

(3) pressure difference across the ejector,

(4) thrust from ejectors (determined by pitot-static traverse and by a target, which must be adaptable to every ejector size),

(5) thrust of exhaust gas only from a critical nozzle should be either estimated or preferably measured by a target.

5.2.4. In the single cylinder tests of the R.A.E. Low Drag Power Plant, which includes a double exhaust ejector, explosions occurred in the exhaust gas-cooling air system. It is thought at present that these explosions are due to the spontaneous ignition of the CO - H_2 - air mixture. Since they can be expected to occur in any similar ejector arrangement, experimental work should be undertaken in order to find under what condition they occur and to find means of eliminating them.

6. Bibliography

No.	Author	Title, etc.
1	Bailey A., Wood S.A.	High speed induced wind tunnel. R. & M. 1468, 1932.
2	Beeton A.B.	A theoretical calculation of the reduction in drag obtainable by ejector action of the exhaust gases when mixed with the cooling air-flow of a typical air-cooled engine. R.A.E. Tech. Note Eng.344, April, 1945.
3	Berry J.R., Irving D.E.	Application of jet augmentation to turbo-supercharger installations. Memorandum Report, Army Air Forces (U.S.A.), Materiel Command, Engineering Division, 20th March, 1944.
4	Bristol Aeroplane Co. Ltd., Engine Division	The possibilities of jet ejectors. Memorandum KR/65, 15th February, 1944.
5	Campbell P.J.	Ground tests of exhaust gas thrust augmentors. United Aircraft Corp., Research Division, Report R-50, 20th November, 1940.
6	Campbell P.J.	Tests of exhaust propulsion nozzles. United Aircraft Corp., Research Division, Report R-309, 11th December, 1942.
7	Flügel G.	The analysis of jet pumps. N.A.C.A. Tech. Memo. 982, 1941.
8	Hawthorne E.P., Zaporski B.	Exhaust ejector tests on a Merlin 46 engine.

No.	Author	Title, etc.
9	Howell A.R.	Note on the theory of simple thrust augmentors for jet propulsion. R.A.E. Note E.3886, August, 1941.
10	Hudson, Saunders, Broughton	Thrust from ejector exhausts. A.R.C.7843, ICE.1630, 1944.
11	Jacobs, Shoemaker	Tests on thrust augmentors for jet propulsion. N.A.C.A. Tech. Note 431, September, 1932.
12	Karman T., Hsue-Shen T., Canright R.	A study of the possibility of using the ejector action of the jet as a source of power for driving propellant pumps. Air Corps Jet Propulsion Research, U.S.A. Galcit Project No.1, California Institute of Technology, 27th July, 1943.
13	Keenan J.H., Neumann E.P.	A simple air ejector. Paper for presentation at A.S.M.E. annual meeting, December, 1941.
14	Kort L.	Raketen mit Staahlapparat, Zeitschrift fur Flugtechnik und Motorluftschiftfahrt, August, 1932.
15	Kuethe A.M.	Investigations of the turbulent mixing regions formed by jets. Journal of Applied Mechanics, September, 1945.
16	Lee J.G.	Progress report on augmented jet propulsion. United Aircraft Corp, Research Division, Report R-48, 21st October, 1940.
17	Manganiello J.	A preliminary investigation of the exhaust gas ejectors for ground cooling. A.R.C. 6136, ICE.1485, September, 1942.
18	Manganiello J., Bogatsky D.	An experimental investigation of rectangular exhaust-gas ejectors applicable for engine cooling. N.A.C.A. ARR. 4E31, May, 1944.
19	Marquardt R.E.	A theoretical and experimental investigation of exhaust ejectors for cooling at low speeds. N.A.C.A. ACR., ARC.7273, July, 1943.
20	Marquardt R.E.	A study of cooling and exhaust disposal in submerged engine installations. N.A.C.A. ACR., ARC.7352, October, 1943.
21	Morrison R.	Jet ejectors and augmentation. United Aircraft Corp., Research Division, Report R-74, 24th October, 1941.
22	Phillips W.H., Rauscher M.	Propulsive effects of radiator and exhaust ducting. Journal of Aeronautical Sciences. February, 1941.

No.	Author	Title, etc.
23	Pinkel, Turner, Voss	Design of nozzles for the individual cylinder exhaust jet propulsion system. N.A.C.A. ACR., ARC.5567, April, 1941
24	Rolls-Royce Ltd., Experimental Dept.	The thrust from multi-ejectors. DCR/PRSN1/FEB, 25th April, 1941.
25	Schubauer	Jet propulsion with special reference to thrust augmentors. N.A.C.A. Tech. Note 442, January, 1933.

Circulation:

D.S.R.
D.E.D.
D.D.S.R.1. (Action copy)
D.D.R.D.I.
R.T.P./T.I.B. (2 + 1)
R.T.P.2a. (80)
Air-cooled Engine Cooling Panel (20)
Director R.A.E.
D.D.R.E.
Aero. Dept.
Library

RESTRICTED

REEL

C 32

FRAME

792

TITLE: Note on Exhaust Actuated Air Ejector Design

CONFIDENTIAL

ATI 792

DIVISION (None)

AUTHOR(S): Lukasiewicz, J.

ORIGINATING AGENCY: Royal Aircraft Establishment, Farnborough, Hants

PUBLISHED BY: (Same)

ORIG. AGENCY NO. TN Eng. 352

PUBLISHING AGENCY NO. (Same)

DATE	DOC. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
June '45	Restr.	Gt. Brit.	Eng.	11	diagrs

ABSTRACT:

The prospects of utilizing exhaust gas energy by applying ejectors as cooling air pumps and thrust augmenters are investigated. The variables of available performance are shown and the theoretical and experimental ejector performance are compared. Estimates of data for basic exhaust thrust and optimum exhaust nozzle areas are considered. No basic rules for adequately determining nozzle areas are available at the present time. Future theorettcal and experimental work on ejectors is suggested. A bibliography of references is attached.

(OVER)

E.O. 10501 dtd 5 Nov 53

DISTRIBUTION: Copies of this report may be obtained only by U.S. Military Organizations

DIVISION: Power Plants, Jet and Turbine (5)
SECTION: Exhaust System and Nozzles (6)

SUBJECT HEADINGS: Nozzles, Exhaust (67001); Thrust augmentation (94200)

ATI SHEET NO.: R-5-6-3

GP-1, AUTH: DOD DIR 5200.10, 23 June 6[illegible]

RESTRICTED

ATI-	792
REVISION	(None)
ORIG. AGENCY NO.	TN Eng 352
PUBLISHING AGENCY NO.	(Same)

TITLE: Note on Exhaust Actuated Air Ejector Design

AUTHOR(S): Lukasiewicz, J.
ORIGINATING AGENCY: Royal Aircraft Establishment, Farnborough, Hants

PUBLISHED BY: (Same)

DATE	DOC. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
June '45	Restr.	Gt. Brit.	Eng.	11	diagrs

ABSTRACT:

The prospects of utilizing exhaust gas energy by applying ejectors as cooling air pumps and thrust augmenters are investigated. The variables of available performance are shown and the theoretical and experimental ejector performance are compared. Estimates of data for basic exhaust thrust and optimum exhaust nozzle areas are considered. No basic rules for adequately determining nozzle areas are available at the present time. Future theoretical and experimental work on ejectors is suggested. A bibliography of references is attached.

DISTRIBUTION: Copies of this report may be obtained only by U.S. Military Organizations

DIVISION: Power Plants, Jet and Turbine (5)
SECTION: Exhaust System and Nozzles (6)

SUBJECT HEADINGS: Nozzles, Exhaust (67001); Thrust augmentation (94200)

ATI SHEET NO.: R-5-6-3

Information Centre
Knowledge Services
[dstl] *Porton Down,*
Salisbury
Wilts
SP4 0JQ
22060-6218
Tel: 01980-613753
Fax 01980-613970

Defense Technical Information Center (DTIC)
8725 John J. Kingman Road, Suit 0944
Fort Belvoir, VA 22060-6218
U.S.A.

AD#: ADA800657

Date of Search: 4 Aug 2009

Record Summary: AVIA 6/8641
Title: Exhaust actuated air ejector: design
Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
Former reference (Department) T.N.ENG. 352
Held by The National Archives, Kew

This document is now available at the National Archives, Kew, Surrey, United Kingdom.

DTIC has checked the National Archives Catalogue website (http://www.nationalarchives.gov.uk) and found the document is available and releasable to the public.

Access to UK public records is governed by statute, namely the Public Records Act, 1958, and the Public Records Act, 1967.
The document has been released under the 30 year rule.
(The vast majority of records selected for permanent preservation are made available to the public when they are 30 years old. This is commonly referred to as the 30 year rule and was established by the Public Records Act of 1967).

This document may be treated as <u>UNLIMITED</u>.